MESSAGE MODE OPERATIONS FOR SPACECRAFT: A PROPOSAL FOR OPERATING SPACECRAFT DURING CRUISE AND MITIGATING THE NETWORK LOADING CRUNCH

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Abstract

The NASA Deep Space Network (DSN) is a world-class spacecraft tracking facility with stations located in Spain, Australia and USA, servicing Deep Space Missions of many space agencies. The current system of scheduling spacecraft during cruise for multiple 8 hour tracking sessions per week currently leads to an overcommitted DSN. Studies indicate that future projected mission demands upon the Network will only make the loading problem worse. Therefore, a more efficient scheduling of DSN resources is necessary in order to support the additional network loading envisioned in the next few years: The number of missions is projected to increase from 25 in 1998 to 34 by 2001. In fact, given the challenge of the NASA administrator, Dan Goldin, of launching 12 spacecraft per year, the DSN would be tracking approximately 90 spacecraft by 2010. Currently a large amount of antenna time and network resources are subscribed by a project in order to have their mission supported during the cruise phase. The recently completed Mars Pathfinder mission was tracked 3 times a week (8 hours/day) during the majority of its cruise to Mars.

This paper proposes an innovative approach called Message Mode Operations (MMO) for mitigating the Network loading problem while continuing to meet the tracking, reporting, time management, and scheduling requirements of these missions during Cruise while occupying very short tracking times. MMO satisfies these requirements by providing the following services:

• Spacecraft Health and Welfare Monitoring Service
• Command Delivery Service
• Adaptive Spacecraft Scheduling Service
• Orbit Determination Service
• Time Calibration Service

Utilizing more efficient engineering telemetry summarization and filtering techniques on-board the spacecraft and collapsing the navigation requirements for Doppler and Range into shorter tracks, we believe spacecraft can be adequately serviced using short 10 to 30 minute tracking sessions. This claim assumes that certain changes would have to be made in the way the Network traditionally services missions in Cruise. Furthermore, limiting spacecraft to short sessions will free up larger blocks of time in the tracking schedule to help accommodate future tracking demands soon to be placed upon the Network.

This paper describes the key characteristics and benefits of MMO, the operational scenarios for its use, the required changes to the ground system in order to make this approach feasible and the results of two simulations: 1) to determine the effects of MMO on projected mission loading on the DSN and, 2) to determine the effect MMO has on spacecraft orbit determination.

Key words: Message Mode Operations, Adaptive Spacecraft Scheduling, Orbit Determination

Introduction

The purpose of Message Mode Operations (MMO) is to utilize DSN tracking time and ground resources more efficiently by making the spacecraft an active partner in the scheduling process. MMO utilizes short 10 minute (minimum) to 30 minute (maximum) unscheduled periods of Deep Space Network (DSN) tracking time based upon spacecraft need and ground availability to determine the health and welfare of the spacecraft, download key engineering telemetry status, determine future scheduling opportunities, uplink a new ground schedule, and obtain necessary Doppler and range data. The purpose of this paper is to introduce and define the concept of MMO and to generate significant preliminary evidence to demonstrate MMO's usefulness as an operational mode for future spacecraft which utilize the services of NASA's Deep Space Network.

Philosophy of Use during Cruise

MMO is applicable during those portions of a mission's cruise phase in which no major activities are scheduled. For the candidate missions under study, this equates to several months during which spacecraft could operate in Message Mode, see Table 2. Activities such as instrument calibrations, and maneuvers which require longer tracking passes and two-way tracking are outside the scope of MMO.

Philosophy of Use during Extended Mission

MMO may also be used during the extended mission, since like the majority of the cruise phase, no major activities are scheduled. MMO telemetry could provide a science preview capability by means of thumbnail sketches of science opportunities for evaluation by the ground or on-board. Promising opportunities could result in the spacecraft generating a service request for a future tracking support.

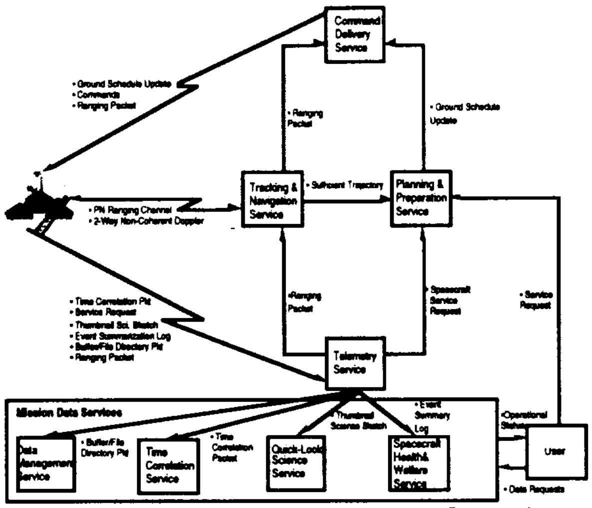

Figure 1: Context of Message Mode Operations

Message Mode Operations Scenario

Figure 1 depicts the key functionality, data flows, and ground services involving Message Mode Operations. There are two major techniques for MMO spacecraft to communicate with the ground: hunting mode, and scheduled mode. The technique chosen will be a function of how frequently a spacecraft can transmit its MMO telemetry due to spacecraft resource constraints and how available the ground system is for tracking MMO spacecraft. The first technique, called hunting mode, is unscheduled and attempts to make use of short uncommitted antenna time that would normally go unutilized. In this mode, the ground attempts to make contact with multiple MMO spacecraft in a limited region of the sky over a 20 to 40 minute period. These MMO spacecraft have been receiving updates to the ground schedule and, therefore, have a model of when the ground is most likely to listen in including potentially the ground search priority. The second technique involves scheduling MMO tracks for those spacecraft whose mission needs require a guaranteed contact time. It is believed that most spacecraft could make use of hunting mode, given the reduced activity profile of most missions in Cruise.

The spacecraft and ground maintain a two-way non-coherent link from which both one-way Doppler and *coupled non-coherent range* are acquired, since an MMO track is too short to acquire a spacecraft in two-way coherent mode. The Tracking and Navigation Service processes these radiometric data and produces a trajectory sufficient to meet the less demanding tracking requirements of the spacecraft being serviced during Cruise or during extended mission. See the section, *MMO effect on Orbit Determination* for more details.

The trajectory is used by the Planning and Preparation Service as the trigger to produce the view periods file, frequency predicts, light time files, etc. required to support the tracking of the spacecraft. This service also produces the ground tracking schedule for all spacecraft, as well as receives requests for service from MMO spacecraft and from users. Service requests from the spacecraft and ground users may affect the current ground schedule and, therefore, a provision is made for uplinking future schedules and changes to these schedules via the Command Delivery Service. MMO spacecraft must be capable of accepting these updates during any uplink. The spacecraft validates these changes to the ground schedule and stores them on board as ground session windows. In general, commands, if necessary, as well as the ranging packet, providing the time tag when the last range measurement was received by the ground, along with the phase of the pseudo-range code at that time instant, are also uplinked.

On the downlink, the spacecraft telemeters all essential information in order for mission operations to 1) ensure the correct trajectory of the spacecraft, 2) maintain the time correlation between spacecraft time and UTC, 3) field service requests from the spacecraft indicating extended or future supports, 4) examine thumbnail science sketches providing the opportunity for quick look data interpretation and further science harvesting by issuance of a service request for further tracking, 5) monitor spacecraft buffer and/or file directory status via the telemetered buffer/file directory packet (Operations uses this directory to make decisions on what files need be downloaded during future tracks), 6) interpret the health, welfare, and state of the spacecraft by viewing the event summarization log, 7) provide to both the ground system, as well as the spacecraft, the capability of calculating the one-way range measurement from the range packet.

Table 1: Roadmap to MMO

Key Functions	Current DSN Design/Performance	MMO Enabler	Required MMO Design/Performance
[redacted]			
Spacecraft - Ground Scheduling	Spacecraft is a passive entity in the scheduling process. Ground schedules the spacecraft.	Spacecraft becomes an active partner in the scheduling process.	Automated Ground scheduling system uplinks scheduled tracking sessions and future potential sessions. Spacecraft provides times it has scheduled for other activities, reviews uplinked proposed schedules and downlinks service requests.
[redacted]			
MMO capable spacecraft	Closest thing to MMO is Beacon mode currently being prototyped on DS-1, in which 4 distinct subcarrier frequencies signals 4 separate spacecraft states.	Demonstrated MMO ground system capabilities.	Spacecraft must accept and store ground schedule, updates to that schedule, and generate its own service requests.

Roadmap to MMO

The key functions within the current DSN that require change in order to enable MMO are: 1) Significant reduction in pre and post calibrations, 2) spacecraft-ground scheduling, 3) one-way radiometric data types and their weighting for orbit determination during Cruise, and 4) the creation of autonomous MMO capable spacecraft.

The current system requires a long pre and post calibration period (see row 1, Table 1) in order to prepare a station for a track and ensure that the equipment remains within specification after the track. The short MMO track practically limits pre and post calibrations to 30 minutes total. As the station moves towards more automation through the service system design process, it is believed that both pre and post calibrations will be reduced to less than 30 minutes total. It is critical to note that the pre-calibration period is largely driven by the calibration of the ranging system. Alternative methods for doing range calibrations, such as calibrating during the track and reducing the time of a range measurement to 1 minute should enable the Tracking and Navigation Service System to achieve the short goal.

The current system provides a forum working within the resource allocation process (RAP) in which missions negotiate for tracking time amongst themselves. Long term schedule conflicts are resolved between mission representatives during these meetings. The system produces short term (7 day) and long term (8 week) schedules that for the most part mirror the agreements made during the RAP process. MMO requires a much more automated and flexible scheduling system. See row 2, Table 1 below. In order for the short duration MMO passes to be useful, the system is required to find unscheduled periods in an automated fashion. Moreover, the spacecraft becomes an active partner in the scheduling process informing the ground when it needs a track by means of a service request.

Orbit determination is largely accomplished for most missions today based upon two-way coherent communications (Doppler and range) in which the phase of the downlink signal is uniquely determined by the received uplink signal from the ground system. Generally, even in Cruise, the accuracy to which these measurements are made are typically well within the required tolerances of the missions. See row 3, Table 1. The short duration of the MMO, track coupled with the time required to pull the spacecraft oscillator to the required ground tracking frequency, necessitates that Doppler and range be acquired in one-way non-coherent mode. Fortuitously, a new technique, called *coupled non-coherent ranging,* has the potential for providing accurate range measurements within the drift specification of the on-board oscillator. See the section, *MMO Effect on Orbit Determination.*

Currently, spacecraft communicate with the ground under direction of the following 4 scenarios: 1) by immediate ground command, 2) by stored sequence time driven commands, 3) by fault response (emergency modes), or 4) the new beacon mode (see row 4 Table 1). None of these scenarios provides the capability for a spacecraft to automatically schedule itself into the ground tracking system. For MMO to provide for flexible on-demand scheduling, spacecraft will require the capability to submit service requests and receive ground schedule updates. This approach is in line with the Consolidated Space Operations Contract architecture in which spacecraft are to take full advantage of access on-demand and that utilize high levels of autonomy with minimum ground operations support in order to achieve expected cost savings.

MMO Effect on Deep Space Network Loading

The following is a preliminary assessment of how MMO affects the DSN tracking schedule. First, the mission subset over which the message mode operations scenario was applied is presented, followed by the mission cruise tracking requirements and assumptions applied in the study. Finally, the effect on the applicable DSN subnets i.e., 34M High Efficiency (HEF) and 34M Beam Wave Guide (BWG) as a result of applying Mission Mode Operations (MMO) to the scheduling system is reported.

A number of missions were provided as candidates for MMO. Of these missions, a number were not applicable due to limited tracking requirements in cruise. Following is a list of all the missions considered along with the missions included in the study clearly identified:

Table 2: Missions considered/included in MMO Loading Study

[redacted]			
Deep Space 2	1/1999	Consigned with Mars Polar Lander	No
[redacted]			
Genesis	1/2001	Cruise Period 5/01 to 3/04	Yes
[redacted]			
Mars 01 Orbiter	3/2001	Cruise Period 4/01 to 8/01	Yes
[redacted]			
Stardust	2/1999	Cruise throughout study period	Yes

Cruise requirements of the above listed missions were carefully chosen to include those segments that are truly in cruise mode. This means that trajectory correction maneuvers and other activities of a priority higher than Cruise were not considered within a MMO scenario. However, simplifying assumptions about MMO cruise activities would have to be revisited when the detail requirements of the cruise phase of these missions become available. The following assumptions were made concerning the MMO cruise phase of operations:

1. Independent of the current cruise phase requirements, it was assumed that during a MMO cruise phase, at least one contact per day would be required.
2. Improvements in pre and post calibration procedures would conceivably reduce the total calibration time to 30 minutes.
3. The MMO daily contact was assumed to be 30 minutes long.
4. There was no provision made for periodic long tracks during lengthy cruise operations. (This would require detail requirements negotiations with missions operating in the MMO mode.)

Given the assumptions defined above, the JPL Telecommunication and Mission Operations Directorate (TMOD) Resource Allocation Team's FASTER suite of forecasting tools was used to evaluate the effect on the DSN resources given the assumptions for the one MMO scenario above. The following is a description of the results:

Forecast year 2001 was impacted the most by MMO technology. All selected projects operated in a cruise phase for some portion of that year. Each mission's cruise scheduling requirements are unique, which explains the difference in the figure of merit, *increase in antenna time* in Table 3 below. This figure refers to the overall increase in antenna time for a subnetwork as a whole, as a result of a particular mission or group of missions switching to MMO technology. For a particular mission, the increase represents the average increase in antenna time available to that subnet during that mission's cruise period, e.g., if the Mars' 01 Lander switched to MMO, there would be a 9% increase in available 34M BWG time, and a 22% increase in available 34M HEF time. For a group of missions on a given subnet, it represents the average increase in antenna availability within that subnet over their collective cruise periods.

Table 3: Result of Mission Loading Study

[redacted]		
34M BWG	9%	Mars '01 Lander
[redacted]		
34M HEF	22%	Mars '01 Lander
[redacted]		
34M HEF	8%	Mars '01 Lander
[redacted]		
		Stardust
[redacted]		
		Mars '01 Lander
[redacted]		

The 34M HEF subnet benefited the most in terms of increased antenna time available to other missions during the Mars '01 Lander cruise period with an increase of 22%. The maximum growth in antenna time was 33% for three specific weeks during its cruise. Considered collectively, the 34M HEF subnet increased its availability by 8% which was slightly better than the 5% increase in the 34M BWG subnet. The largest contributor to the 34M HEF increase was the Stardust mission.

Table 4: Comparison of Antenna Time and Cost in 2001 (MMO vs Standard Operating Mode)

[illegible]	[illegible]	[illegible]	[illegible]
(name)	(hours)	(real-year $)	(real-year $)
[illegible]	[illegible]	[illegible]	[illegible]
Genesis - MMO	91	$107,748	
[illegible]	[illegible]	[illegible]	[illegible]
Mars 01 Lander - MMO	105	$124,325	
[illegible]	[illegible]	[illegible]	[illegible]
Mars 01 Orbiter - MMO	112	$132,613	
[illegible]	[illegible]	[illegible]	[illegible]
Stardust - MMO	231	$273,515	
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]

Table 4 is the result of running the results of the loading study against the NASA JPL DSN station cost calculation form. The purpose of this exercise was to determine the total tracking hours and associated cost required to track the candidate missions in the study for a given aperture size. The results show an approximate 2.6x reduction in tracking hours for the Genesis mission and a cost savings of $88K, if MMO is used during cruise. For the Mars Surveyor 2001 Lander, tracking time was reduced by approximately 4x, with a cost savings of over $245K. A similar result occurred for the Mars Surveyor 2001 Orbiter. Stardust, on the other hand, showed a total reduction of 8 tracking hours, but an increase in tracking costs of approximately $100K. This is the result of the 7x increase in the number of pre and post-calibrations needed to support MMO 7 days a week as opposed to one six hour track of standard operations during cruise. It is hoped that through experience with MMO a reduction in MMO tracks to every other day or potentially one or two contacts per week can be achieved. Overall, the total delta cost savings due to reduced tracking time during Cruise is approximately $0.5 Million dollars for these 4 missions alone.

MMO Effect on Orbit Determination

Traditionally, orbit determination for deep-space missions has been performed using 4 to 8 hours of tracking per pass with two-way coherent Doppler. In many cases, two-way coherent range measurements are available if the spacecraft transponder design has the capability to receive and transmit a ranging code modulated on the carrier. Optical images of the target body taken by the spacecraft are sometimes used during the final weeks or months leading up to encounter. These optical navigation images are especially powerful if the target's ephemeris is not well known, as is the case with asteroids and comets.

There are generally two requirements imposed on orbit determination for each mission. The first and most important requirement is ensuring that the spacecraft is delivered to the target body within an acceptable level of error sufficient to meet mission objectives such as orbit insertion, flyby reconnaissance, or atmosphere entry and landing. This requirement varies from mission to mission. The second requirement is that at any time during the mission, the spacecraft's ephemeris is known well enough to allow ground stations to correctly point and acquire the spacecraft's signal without searching the sky or sweeping through the spectrum for the downlink carrier frequency. For missions transmitting at X-band, the requirement for accurately pointing the ground antennas is 130 arc-seconds (3-sigma), translating to a maximum position error of approximately 63,000 km at 100 million km distance from Earth[1].

Message Mode Operations would replace the 4 to 8 hours of two-way Doppler data collected per pass with only 10-30 minutes of one-way Doppler. Because in one-way Doppler the reference oscillator is onboard the spacecraft rather than on the ground, the frequency stability of the carrier is worse, resulting in Doppler measurements with 5 to 20 times more noise. Furthermore, onboard oscillators tend to drift with time due to temperature fluctuations and age, so this error must be estimated and removed to avoid obtaining an incorrect orbit solution.

Ranging can be performed with a non-coherent link between the ground and the spacecraft. The ground transmits a range code to the spacecraft, the spacecraft demodulates the code, records the time the range code was received, and re-modulates the signal back on the downlink while transmitting the code receipt time via telemetry. Once the ground receives the re-modulated range code, it has a measurement of both the uplink and downlink delay, and thereby a measure of range (for both upleg and downleg) is obtained. The accuracy of this ranging method measurement is dependent on the onboard clock error, therefore it is important that the spacecraft and ground clocks be synchronized, and the timing difference between them be estimated in the orbit determination process. This ranging technique, dubbed *coupled non-coherent ranging*, has yet to be demonstrated on deep-space missions.

To gauge the effectiveness of orbit determination in Message Mode Operations, a scenario was developed using the Mars Surveyor 2001 Lander as a test case. The Mars '01 Lander will be launched in April of 2001, and arrives at Mars in January 2002 after 9 months of flight and 5 midcourse corrections[2]. Because this mission will employ precision landing techniques for the first time at Mars, it is vital that the flight path angle upon atmosphere entry be kept to a minimum. The baseline navigation plan calls for

two-way coherent tracking throughout cruise, starting with 3 passes per day for the first 8 days, then decreasing to 3 passes per week for 7 months, then returning to three per day 60 days before arrival. All passes are a minimum of 4 hours each, collecting two-way coherent Doppler and range every 10 minutes from the 34-meter stations located in Australia, California and Spain.

For the MMO case, all passes from Launch+8 days to Landing-60 days were reduced to only 30 minutes each per day. During these passes, one-way Doppler and coupled non-coherent range was simulated with noise values of 1.0 mm/sec and 100 m. respectively. The tracking data at the beginning and end of cruise (first 8 days and final 60 days) remained unchanged from the baseline case.

Figure 2 is a logarithmic plot showing the results. The two lines at the bottom are the root-sum-squared (RSS) position uncertainty resulting from orbit determination during cruise for both the baseline and Message Mode Operations cases. For each data point on the graph, tracking data up to that time is processed, and the resulting orbit determination error is mapped to the Earth-centered J2000 coordinate frame at that time. The gray line at the top indicates the maximum tolerable error in position in order to correctly track the spacecraft. As can be seen, the two cases start with identical uncertainties during the first 8 days of cruise where two-way data is available in both scenarios. At the second point in the graph, the MMO scenario starts using one-way data and, as expected, the uncertainty grows with respect to the baseline case. The maximum uncertainty occurs near September 18th, when the MMO case has an uncertainty of 850 km, yet this uncertainty is well below the maximum error requirement. Therefore, this figure indicates that Message Mode Operation tracking provides sufficient data for orbit determination for routine tracking.

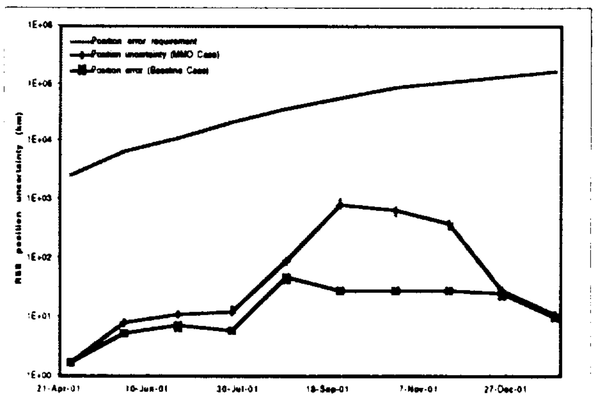

Figure 2: Orbit Determination Uncertainties During Cruise for the Mars 2001 Lander

Figure 3 shows a B-plane projection of the orbit determination error 30 days before encounter for three cases; the baseline case, the MMO case (entitled "MMO case: two-way near encounter"), and a version of MMO that includes no two-way tracking ("MMO case: one-way near encounter"). This figure is meant to illustrate how confidently each mode can deliver the spacecraft to the desired target for atmosphere entry. The baseline case provides the smallest uncertainty ellipse (45 km x 10 km) since it uses the highest quality of tracking data and at greater quantity. The MMO case with two-way near encounter is approximately 50% longer (75 km x 10 km), and the MMO case with one-way near encounter is much larger (350 km x 10 km).

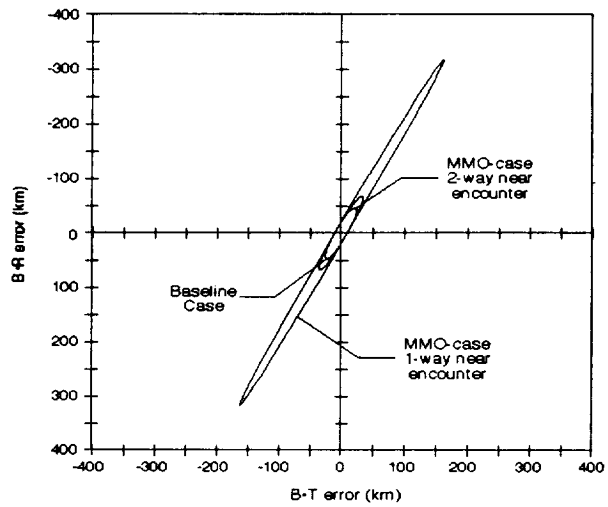

Figure 3: Orbit Determination Results at Mars-30 days mapped to B-plane

The consequences of the largest of the three ellipses to the Mars '01 Lander mission would be a significantly higher probability of entering the atmosphere too steep and impacting the surface too hard, or entering too shallow and missing the landing site, or worse, skipping out of the atmosphere completely. Therefore, while brief, 30-minute one-way tracking passes available through MMO are sufficient for routine navigation during cruise, MMO alone is insufficient to satisfy the tight delivery requirements needed for missions like the Mars '01 Lander. In order to meet these delivery requirements, MMO would have to be followed with a traditional campaign of two-way tracking, or augmented with optical navigation images near encounter.

It's important to mention that one of the reasons current missions require long passes of tracking data is that, for various reasons, the navigation analysts typically discard 10-20% of the data as unusable for orbit determination. Since MMO yields far less data, each data point is therefore more "valuable" in the MMO case. The tracking system of the future will therefore need to be improved to provide a much higher tracking system reliability, so that less than 1% of all tracking data are considered unusable.

Future studies of MMO on orbit determination could examine the effect of reducing the number of passes per week, reducing the length of a MMO pass from 30 minutes, and also adding an Ultra-Stable Oscillator (USO) onboard the spacecraft to improve the Doppler quality.

Conclusions

The following conclusions are drawn from this study on MMO:

• It appears that tracking savings up to $0.5 Million dollars can be achieved if MMO is utilized for Genesis, Stardust, Mars '01 Lander and Mars '01 Orbiter during their cruise phases.

• It appears that extensive passes, i.e., 4 to 8 hours of two-way coherent radiometric data, are not required to meet the Mars '01 Lander cruise tracking requirements, provided a technique like MMO can be substituted.

• MMO alone is insufficient to satisfy the tight delivery requirements needed at encounter for missions like the Mars '01 Lander.

• There appears to be enough of a cost benefit to merit a complete study of MMO by JPL's TMOD for future spacecraft such as the X2000 program.

• If cost and time savings are found to be significant for the majority of future missions along with meeting their navigational requirements then the next series of functional requirements on JPL's TMOD Network Simplification Project (NSP) should reflect MMO requirements.

• JPL's DSN will begin charging projects for antenna time. In the past, antenna time was negotiated between projects and prioritized based upon mission phases and emergency needs. Prioritization of antenna time is now a factor of economics as well as mission needs. In general, MMO may allow for tracking of more missions, since it appears to make better use of antenna tracking time. Therefore, it may aid in sustaining the expected increase in the mission set.

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